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ABSTRACT

This document reports on an educational research study directed towards identifying components necessary for the design of instructional programs to teach problem solving to students in grades 2-8. Thirty eighth grade students utilizing a geology unit from the Individualized Science (IS) program participated in the pilot study reported here. Results indicate knowledge, the interaction of knowledge and process, and other factors such as the ability to recognize and define terms and the ability to identify relationships among terms contributed to final scores obtained. (SL)

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A CLASSROOM STUDY OF THE INFLUENCE OF SCIENCE KNOWLEDGE STRUCTURES ON CHILDREN'S SUCCESS IN SOLVING ACADEMIC PROBLEMS

by

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Introduction

This study explores certain aspects of the relationship between representations of students' knowledge structures of science subject matter and their success in solving verbal academic problems. The students are eighth graders, the subject matter is descriptive geology, and the problems are verbal analogies and set-membership tasks.

The research reported here relates to the long-term research goal of the Scientific Problem Solving and Inquiry Project of the Learning Research and Development Center, viz., to identify components and processes necessary for the design of instructional programs to teach science problems to students at the elementary and middle school levels. The focus of our initial work has been to determine methods for probing students' knowledge structures, to relate representations of student knowledge structures to problem-solving competence, and to assess the congruence between science content structures as represented in science instructional materials and changes in the representations of knowledge structures of students after exposure to instructional materials.

Our research bridges the theories and research paradigms of cognitive psychology and the technology of instructional design. We view ourselves primarily as science educators, actively engaged in bringing psychological theory and research to bear on science instruction.

Knowledge structures and their relationships to problem solving are areas of active theoretical speculation and empirical research in the field of

cognitive psychology. Several individuals (e.g., Johnson, 1971; Shavelson, 1974) who have made important theoretical and methodological contributions to the research on science knowledge structures have pointed out that the knowledge derived from this work has important implications for instruction. Nevertheless, differing perspectives on the relationship between knowledge structures and problem solving are evident in the literature. Paul Johnson (1969) suggests that more can be learned about the extent to which an individual understands a portion of science content by analyzing that individual's representation of the relationships among the important concepts related to the content area than by asking the student to solve problems. Conversely, Bhaskar and Simon (1977) states the importance of knowledge structures to the ability to solve problems.

The theoretical and empirical links between analogies and knowledge structures has been discussed in the recent literature of cognitive psychology. Investigators such as Greeno (197), have studied the reasoning skills involved in solving analogies and have begun to establish links between these skills and other mental operations, especially those frequently associated with problem solving. Analogical reasoning is described essentially as a rule induction process in which an individual searches for relationships among concepts, i.e., constructs a concept structure. Thus, such processes play an important role in the development of concepts and of "knowledge networks."

Set-Membership tasks are a type of verbal problem that has not been used often, if at all, in studies of knowledge structures. These tasks have features similar to verbal analogies. An example of a set membership task is the following: Put an X on the word that does not belong in this set: Eight Two Apple Five. Students must "search their knowledge structures"

for relations that link concepts. Set membership tasks contain the added difficulty, however, that the individual is not provided with the "hint" of which terms "contain" the "hidden" relationship. Instead he must search all four or five terms for the pertinent relationship.

The previous work done in investigating science knowledge structures and their relationships to problem solving has been done with college and high school students and has used content from highly formalized science disciplines; e.g., mechanics (Johnson, 1971; Shavelson, 1974), mathematics (Geeslin, 1975), and thermodynamics (Bhaskar & Simon, 1977). Our investigations have been done with 6th, 7th, and 8th graders, and we have used content from a much less formalized discipline, descriptive geology.

Procedure

Instructional Materials, Setting, and Sample

The instructional materials used in this research deal with the subject of minerals and rocks, and consist of a segment of the field-testing version of the Lyell Unit of the Individualized Science program (Champagne and Klopfer, 1974, 1972-1975). The Lyell Unit includes aspects of descriptive, historical, and physical geology. The Invitation to Explore (ITE) Minerals and Rocks is primarily descriptive geology. The student's booklet for the ITE is 67 typewritten pages long, and consists of reading text, manipulative activities, and student self-administered progress tests. On the average, a student completes the ITE in three to four weeks with five 45 minute periods per week.

The ITE Minerals and Rocks was designed to incorporate structural features of the content of descriptive geology. The structural relations include hierarchical class-inclusion, transformational, and definitional relations. The ITE is organized, in part, around the definition of a mineral and the taxonomic

classification of rocks. The two most important structural relations, one hierarchical and the other transformational, are the classification of rocks on the basis of how they form and the rock cycle through which each of three kinds of rock--igneous, metamorphic, sedimentary--can be transformed into either of the other kinds.

The ITE begins by setting a structural context for the student. The content structure is described in the text and is represented visually with a drawing that illustrates both the hierarchichal relationships among major concepts and examples of the concepts. The introductory narrative summarizes these relations. They are elaborated on throughout the text of the ITE. Transformational relations are another major structural feature represented in the text of the ITE. The design of our instruction in the ITE Mineral and Rocks was executed with structural principles explicitly in mind to facilitate the student's learning and retention of the science concepts. However, as suggested in the introduction of this report, we also did this with an eye toward the proposition that structural learning facilitates students' problem-solving abilities.

The study was carried out in a sectarian elementary school, located in a large city. The school's approximately 400 students in grades K through 8 come from middle class homes in the immediate neighborhood. Class size typically ranges between 25 and 35 students.

The science teacher selected 30 students, 17 female and 13 male, from the eighth grade classes to participate in the study. None of these students had previously received instruction in geology. All students had previously studied other units in the Individualized Science program. These units utilize self-instructional materials similar to the ITE Minerals and Rocks. Consequently, all students were familiar with the mechanics of using the instructional materials.

Pre- and Post-Tests, and Concept Structure Analysis Tasks

The study followed the pattern outlined below.

1. Pre-instructional Concept-Structure Analysis tasks probing for structural knowledge about atoms and molecules, minerals, and rocks.

2. Pre-test on science content contained in the ITE, analogies, and set membership.

3. Instruction using the ITE Minerals and Rocks.

4. Post-test--same as pre-test.

5. Post-instructional Concept-Structure Analysis tasks--same as pre-instructional tasks.

The study was carried out over a period of six weeks, with one week for administering the Concept-Structure Analysis tasks both before and after four weeks of instruction. A three-part test was administered just prior to instruction as a pre-test and again when instruction was completed as a post-test. The three parts of the pre- and post-tests consisted of: (1) a standard, multiple-choice item test covering the science content of the ITE Minerals and Rocks, (2) a 17-item analogies test of key terms used in the instructional materials, (3) a 12-item set membership test where each item contains a set of four terms, one of which the student had to identify as not belonging to the set. (Representative items from parts 2 and 3 are shown in Tables 6, 7, and 8 below.) The pre- and post-tests differed only in part 1, which contained 45 item responses on the pre-test and additional responses on the post-test. These tests were administered by the classroom teacher.

The Concept-Structure Analysis tasks were administered in three parts. The first part probed students' knowledge structures of prerequisite science concepts, i.e., concepts the designers presumed students comprehended and which were necessary for comprehension of the science content in the ITE

Minerals and Rocks. The second part probed structural knowledge of minerals, and the third part concerned structural knowledge of rocks. For each task, we used a different set of cards, on which the concepts were printed.

The Concept-Structure Analysis Tasks were individually administered by a single experimenter in the following manner. Each student was told of the purpose of the study and was then led through a practice task that consisted of cards containing familiar anatomical terms. The terms included in each set are listed in Figure 1 under their respective headings: Practice Task, ATOM Task, MINERAL Task, and ROCK Task. For both the practice task and each succeeding task, the student was shown the set of cards and asked if(s)he recognized each term in the set. Then, using the recognized terms, the student was told that the object of the task was to arrange the cards in a way that would show "how you think about the words." The arrangement was laid out on a large piece of paper (28 x 41 cm) and the cards, which had an adhesive on their reverse sides, were pressed into place. The student was then asked to explain why he or she arranged the words in this particular way. The responses were recorded by drawing lines on the paper between cards designated by the student and writing in the relations between words as described by the student. The procedure for administering the Concept-Strucutre Analysis task was the same before and after instruction, except that it was unnecessary to conduct the practice task on the post-instructional administration.

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INSERT FIGURE 1 ABOUT HERE

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Methods of Analysis

Analysis of Knowledge Structure Representations

Devising a reasonably objective method for analyzing salient characteristics of the knowledge structure representations generated by the students presented a considerable challenge. The method we devised depends on ascertaining, the degree of correspondence between students' structures and an "expert" structure. The expert structure is developed by individuals knowledgeable about geology and the instructional materials used in the study. The degree of correspondence between student and expert structures is ascertained by assessing the extent to which certain crucial attributes of the expert structure are present in the student structure. First, from a careful analysis of the expert structure, we prepare qualitative descriptions of the crucial attributes it exhibits. Then we search the student structure for the attributes and, depending on whether they are present or absent, we assign the student structure to one of several structure classes. These structure classes, which are defined chiefly on the basis of the crucial attributes of the expert structure, are arranged in order of increasing complexity. In the lowest structure class, the organizing attribute is simply some graphemic property common to the words themselves. In the more complex classes, the words are treated as concepts and it is the concepts which are structured according to various attributes that relate them. A different series of structure classes has to be defined, of course, for every set of concepts presented in a Concept Structure Analysis task.

For both the ROCK and MINERAL concepts which were used in our structuring tasks, we carried out analyses of the knowledge structure representations as outlined in the preceding paragraph. A detailed description of how we analyzed the ROCK concepts and defined the ROCK structure classes is given in Champagne et al. (1977). From that analysis, we reproduce here

the expert structure for the ROCK concepts (Figure 2) and the chart summarizing the ROCK structure classes (Figure 3). The analysis of the MINERAL concepts is given in the following paragraphs.

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INSERT FIGURES 2 and 3 ABOUT HERE

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MINERAL Structuring Task

Given the words and phrases of the MINERAL Concepts Structuring Task, (see Figure 1), the definition of a mineral provides one major structure, which is shown in Figure 4. Mineral class membership and non-membership relations form a second structure, shown in Figure 5. The hierarchical relations that exist between a specific kind of rock, the minerals of which the rock is composed, and the minerals' chemical compositions, expressed using both a chemical name (e.g., calcium carbonate) and a chemical formula (e.g., $CaCO_3$), define a third structure. This hierarchical structure is illustrated in Figure 6. (Although this structure is designated "hierarchical," it should be noted that it is composed of two different relations. Limestone physically contains calcite crystals. Calcite "contains" calcium carbonate in the sense that, upon chemical analysis, the mineral calcite will be found to consist of calcium carbonate, which is presumed to mean molecules of calcium carbonate.

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INSERT FIGURES 4, 5, and 6 ABOUT HERE

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The structure in Figure 7 is a representation reflecting the chemical relationships among the words, as contrasted with the geological relationships represented in Figure 6. Note particularly that from a chemical perspective, calcite, limestone, and sea shells are roughly analogous, while geologically they are quite distinct. Figure 8 depicts graphically how the chemical

properties of several substances are compared with the properties that define the characteristics of minerals to determine whether or not the substance in question is a mineral.

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INSERT FIGURES 7 and 8 ABOUT HERE

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The integration of the six structures shown in Figures 4 through 9 into one expert structure is somewhat easier to perform "in the head" than on paper. As we have done it (Figure 9), many of the subtleties of the six separate structures are no longer evident. Nevertheless, this integrated structure does depict all the essentail relationships shown in the separate structures and, therefore, can serve satisfactorily as the expert structure. By analyzing this expert structure, we can identify the crucial attributes exhibited in it and prepare a qualitative description of these. Using the descriptions of the attributes, we designate a series of structure classes for the MINERAL Concepts Structuring Task. A summary of these MINERAL structure classes is shown in the chart of Figure 10. This chart is similar in form to the one shown in Figure 3 for the ROCK structure classes, and the function which the two charts serve for us is the same.

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INSERT FIGURES 9 and 10 ABOUT HERE

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Identification of High- and Low-Structuring Groups

The main purpose of our analysis of knowledge structure representations is to establish a means by which "high" structuring students and "low" structuring students can be identified. Once a series of structure classes has been designated for a set of concepts, we can use the descriptions of the classes to decide which attributes student structures must display to classify them as high or low structurers. Since two series of structure classes were

constructed, one for the ROCK concepts (Figure 3) and another for the MINERAL concepts (Figure 10), corresponding high- and low-structuring groups were identified.

For the ROCK Concepts Structuring Task, high structurers were those students whose structures displayed attributes equal to or greater than those of class W-5 on the ROCK structure classes (see Figure 3). The criterion for low structurers was a rating of less than or equal to class W-3 on the post-instructional ROCK task and a rating of less than class W-3 on the pre-instructional ROCK task.

For the MINERAL Concepts Structuring Task the only student whose MINERAL structure was rated as class W-5 or W-6 (see Figure 10) on the pre- or post-task was designated a high structurer. A student who was rated as class W-3 or lower on both the pre- and post-task was designated a low structurer.

Analyses of Scores and Items

The three parts of the written test we administered before and after instruction yielded scores for each student's performance on items testing for Geology Knowledge (part 1) and on two kinds of verbal problem items, Analogies (part 2) and Set-Membership (part 3). We also obtained each student's I.Q. score, based on a recent administration of the Otis-Lennon Mental Abilities Test. For every score, the usual descriptive statistics were calculated for the total group of students, as well as the product-moment correlations between every pair of scores. Using a t-test for correlated groups, we tested the significance of the difference between the means before and after instruction on each score. The same sequence of analyses was repeated four times: for students who were identified for the high-structuring group on the basis of the ROCK Concepts Structuring Task,

for students who were so identified for the low-structuring group, and for the high- and low-structuring groups of students identified on the basis of the MINERALS Concepts Structuring Task. Using a t-test for independent groups, we tested the significance of the difference between the means of the high- and low-structuring groups on each score.

In addition to obtaining students' scores on the verbal problem parts of the written test, we also tallied the number of correct and incorrect responses for each of the 17 Analogies Items and each of the 12 Set-Membership Items both before and after instruction. Using these tallies, we tested the statistical significance of the pre- to post-instructional changes in responses for each item by means of McNemar's chi-square test of change (McNemar, 1964). To compare the performances of the high- and low-structuring groups of students on each of the Analogies and Set-Membership Items, we calculated the proportion of correct responses for each group and tested the statistical significance of the difference between proportions by using a chi-square test. This was done for both pre- and post-instructional administrations of the written test and for the groups identified by both the ROCK and the MINERALS Concepts Structuring Tasks. We used the four comparisons thus available to identify those items on which high-structuring students tend to perform better than low-structuring students. These analyses of individual items provide more detailed information about students' performance than the scores for a whole set of items.

Findings

Pre- to Post-Instructional Changes in Scores

In this and the following two sections, we present the results of analyses of nine score variables, viz.:

Geology Knowledge Items--consisting of items administered both before and after instruction to test the students' knowledge of the geology subject matter in the ITE Minerals and Rocks; maximum possible score: 45.

Variable 1 - Pre-instructional score

Variable 2 - Post-instructional score

Geology Knowledge Percent--percentage of correct responses on the geology knowledge pretest with a total of 45 points and on the geology knowledge posttest with a total of 62 points; maximum possible score: 100.

Variable 3 - Pre-instructional score

Variable 4 - Post-instructional score

Analogies Items--maximum possible score: 17

Variable 5 - Pre-instructional score

Variable 6 - Post-instructional score

Set-Membership Items--maximum possible score: 12

Variable 7 - Pre-instructional score

Variable 8 - Post-instructional score

I.Q. - Variable 9

For each of the nine variables just described, the means and standard errors for all 30 students in the study are presented in Table 1. This table also shows the pre- to post-instructional changes in mean scores on Geology Knowledge Items, Geology Knowledge Percent, Analogies Items, and Set-Membership

Items. The statistical significance of each of these changes was tested using a t-test for correlated means, and the results of these tests also are shown in Table 1. We found that the pre- to post-instructional gains in mean scores were statistically significant ($p < .01$) for Geology Knowledge Items, Geology Knowledge Percent, and Analogies Items, but there was not a significant gain at the .05 level for the Set-Membership Items.

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INSERT TABLE 1 ABOUT HERE

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Comparisons of High- and Low-Structuring Groups

As described in the discussion of our methods of analysis, we identified 10 students in the high-structuring group and 12 students in the low-structuring group on the basis of the ROCK Concepts Structuring Task. For these two groups, the means and standard errors for all nine variables are presented in Table 2. This table also shows the results of the t-tests used to test the statistical significance of pre- to post-instructional changes in mean scores.

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INSERT TABLE 2 ABOUT HERE

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The statistical significance of the difference between the means on each variable for the high- and low-structuring groups was tested using a t-test for independent means. The results of these tests are presented in Table 3. Using these results and those shown in Table 2, we can compare the several scores obtained by the high- and low-structuring groups that we identified from the ROCK Concepts Structuring Task.

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INSERT TABLE 3 ABOUT HERE

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Before instruction the high-structuring group performed better than the low-structuring group (difference between means significant at the .05 level) in both the Geology Knowledge Items and Geology Knowledge Percent scores.

For both scores the pre- to post-instructional gains in the means were statistically significant for both groups, but the low-structuring group improved more than the high-structuring group. Consequently, the post-instructional differences between the means for both the Geology Knowledge Items and Percent scores for the two groups are not statistically significant ($p > .1$). We observe a similar result for the Analogies Items score. Here the high-structuring group's pre-instructional mean is significantly higher ($p < .01$) than the mean of the low-structuring group, but the latter group's pre to post gain is statistically significant ($p < .01$) while the high-structuring group's gain is not. Consequently, the post-instructional difference between the means of the two groups on the Analogies Items is not statistically significant at the .05 level.

The high-structuring group also outperformed the low-structuring group on the Set-Membership Items score before instruction (difference between means significant at the .05 level). Here, however, the pre- to post-instructional gain was statistically significant ($p < .05$) for the high-structuring group while the low-structuring group did not gain. The post-instructional difference between the means of the two groups on the Set-Membership Items is significant at the .01 level. Finally, the difference between the two groups' means on the I.Q. score is significant at the .05 level.

In addition to designating high- and low-structuring groups of students on the basis of the ROCK Concepts Structuring Task, we also employed the student response structures from the MINERALS Concepts Structuring Task to identify high and low groups. Using the criteria described in the discussion of our methods of analysis, we identified 9 students in the high-structuring group and 10 students in the low-structuring group on the basis of the MINERALS Concepts Structuring Task. Of these 9 high-structuring group students, 5 also were members of the high-structuring group of ROCK Concepts,

and of the 10 low-structuring group students on MINERALS Concepts, 7 also were in the low-structuring group on ROCK Concepts. While the overlap in membership of the high- and low-structuring groups based on the two Concept Structuring Tasks is considerable, the performance of the high and low groups on MINERALS Concepts was somewhat different from the high and low groups on ROCK Concepts on the nine variables for which scores were obtained.

In Table 4 we present the means and standard errors for all nine variables and the significance tests for pre- to post-instructional changes in mean scores of the high- and low-structuring groups on the basis of the MINERALS Concepts Structuring Task. Table 5 shows the significance tests for the difference between the means on each variable for the high- and low-structuring groups.

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INSERT TABLES 4 AND 5 ABOUT HERE

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The first four lines of Table 5 show that the means of the high-structuring group for both Geology Knowledge Items and Geology Knowledge Percent scores were higher than the means of the low-structuring group both before and after instruction, but neither difference is statistically significant ($p > .1$) on either occasion. Nevertheless, as Table 4 shows, both groups made statistically significant pre- to post-instructional gains in mean scores for both Geology Knowledge Items and Geology Knowledge Percent. Both groups also made statistically significant gains in the means for the Analogies Items scores from before to after instruction. However, we see in Table 5 that the difference between the means of the high- and low-structuring groups for the Analogies Items scores is not statistically significant at the .05 level either before or after instruction.

For the Set-Membership Items scores, the difference between the means of

the high- and low-structuring groups is statistically significant ($p < .01$) before instruction, as well as after instruction. The pre- to post-instructional gain in the mean score of the high-structuring group is significant at the .05 level, but there is no change in the mean score of the low-structuring group. Finally, comparing the mean I.Q. scores of the high- and low-structuring groups based on the MINERALS Concept Structuring Task, we see that their difference is not statistically significant ($p = .1$).

Summary of Score Comparisons

The three pre- to post-instructional gains in mean scores which are statistically significant for the total group (Table 1) also are statistically significant for each high- and low-structuring group (Tables 2 and 4), whether identified on the basis of the ROCK Concepts or the MINERALS Concepts Structuring Task. Thus, improvement from before to after instruction was made in the Geology Knowledge Items, Geology Knowledge Percent, and Analogies Items scores for both the high-structuring and the low-structuring students. The findings are different, however, for the Set-Membership Items score. Here, the pre- to post-instructional gains in mean scores are statistically significant for the high-structuring students, identified by either set of concepts, but no statistically significant improvement is shown by the low-structuring students.

We also have four mean scores that compare high- and low-structuring students' success in solving verbal problems. When the groups are identified on the basis of the ROCK Concepts Structuring Task, the high-structuring group performs significantly better than the low-structuring group in three of the four instances, viz., on the Analogies Items before instruction and on the Set-Membership Items both before and after instruction (Table 3). When the groups are identified on the basis of the MINERALS Concepts Structuring

Task, the high-structuring group performs significantly better than the low-structuring group in two of the four instances, viz., on the Set-Membership Items before and after Instruction (Table 5). We also note in Tables 3 and 5 that in those instances where the mean score of the high-structuring group on the Analogies or Set-Membership Items is not significantly different at the .05 level from the mean score of the low-structuring group, the observed difference does approach this level of statistical significance. The probability of obtaining a t-value as large as the one calculated is less than .10 in each of these instances. All in all, the comparisons of mean scores provide some positive evidence that students identified as being in a high-structuring group are more successful in solving verbal problems than students in a low-structuring group.

Analysis of Analogies and Set-Membership Items

For each of the 17 analogies items and 12 set-membership items we compared the pre- and post-instructional performance of students in the total group by using chi-square to test the significance of the changes in correct and incorrect responses to the item. Table 6 displays those items for which the test of change yields a statistically significant chi-square (ndf = 1) at the .05 level or less. It is interesting to note that there is a statistically significant pre-post gain for only 3 of the 17 analogies items, even though the pre-post change in the Analogies Items mean score (see Table 1) shows an increase of more than 2 items correct and is statistically significant at the .01 level. This gain in the mean score for all students, then, is due primarily to modest (i.e., not statistically significant) improvements distributed among many of the analogies items.

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INSERT TABLE 6 ABOUT HERE

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Examination of the items in Table 6 also reveals two other noteworthy

features. First, for the 3 analogies items which showed a statistically significant pre-post gain, the improvement can reasonably be attributed to specific knowledge which the students probably acquired from studying the ITE Minerals and Rocks. For example, with reference to the third item, the information that sea shells are composed of calcium carbonate is specifically taught in the ITE. Second, the last item in Table 6 showed a statistically significant pre- to post-instructional loss in the proportion of all students getting it correct. In the information about this same set-membership item given in Table 8 (below), we observe that nearly all of the pre-post loss is probably due to the performance of students in the low-structuring group, whereas the proportion of students in the high-structuring group who give the correct response for this item does not change.

Not only for this one item, but for each of the analogies and set-membership, we sought to determine whether the high-structuring students tend to perform better than the low-structuring students. To do so, we made four comparisons of the proportion of students in high- and low-structuring groups who gave the correct response to each item. We used chi-square to test the significance of the difference between the proportions and chose a p of .20 as the level of significance for this test. For an item to be selected as one on which high-structuring students tend to perform better than low-structuring students, the calculated value of chi-square had to have a p less than .20 in at least two of the four comparisons and a p less than .05 in at least one comparison. The 5 analogies items which met this criterion are displayed in Table 7, while Table 8 displays 7 set-membership items on which high-structuring students tend to perform better than low-structuring students. For each comparison (RI, RF, MI, and MF), the proportion of high- and low-structuring students who gave the correct

response to the item also is shown in the tables. From examinations of the items in Tables 7 and 8, we can obtain some additional insights into possible differences between high- and low-structuring students. These are discussed in the following section.

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INSERT TABLES 7 and 8 ABOUT HERE

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Discussion

A careful analysis of the items that comprise the three parts of the pre- and post-instructional written test indicates that, with very minor exceptions, the items sample terms and relationships from a small, very well-defined content domain. For example, of the 17 analogies items, only 3 contain terms that are not included in the ATOM, ROCK, and MINERAL Concepts Structuring Tasks (see Figure 1). Only one of these analogies items tests a relationship not included in the expert structures of the three tasks. Of the 12 set-membership items, only 2 contain terms not included in the structuring tasks. It is interesting, therefore, to speculate on possible reasons for the observed differences in the total group performance on the Set Membership Items and on the Geology Knowledge and Analogous Items.

The total group amde significant improvement on the Geology Knowledge and Analogies Items, but only the students in the high-structuring groups made significant gains in the Set-Membership Items. This suggests that some factor or factors other than knowledge (i.e., ability to recognize and define the terms and ability to identify the relationships among the terms) contribute to the scores. Moreover, these factors contribute more to the Set-Membership score than to the Geology Knowledge or Analogies score.

We tentatively hypothesize that the processing demands of the set-

membership items are greater than the processing demands for the analogies and that the specific processing ability is related to the process of imposing structure on information. In comparison with the analogies items, the set-membership items are quite unstructured. We hypothesize that to solve the problem which the item presents, the student must literally create a knowledge structure that relates all but one of the terms in the item in a coherent way. It is interesting to note that we have some evidence that students were generating structures using relationships other than those taught in the instructional materials. One set-membership item consists of these terms: calcite, diamond, granite, halite. All the students who got this item wrong selected diamond as their response. This indicates that they had not considered the geologic relationships among the items but had simply noted that three of the terms were related by the common graphemic ending, -ite.

The interesting differences we have noted between students' success in solving the analogies and set-membership items suggests that these verbal problem types might be useful for probing the interaction of knowledge and process in the solution of simple verbal problems.

Table 1

Means and Standard Errors of all Variables for the Total Group and Pre- to Post-Instructional Changes (N = 30)

	Variable	Mean	S.E.	PRE to POST Changes			
				Difference	S.E.	t	p
1	Geol PRE	22.30	0.80				
2	Geol POST	28.43	1.08	+6.13	0.88	6.94	< .01
3	Geol % PRE	54.23	1.95				
4	Geol % POST	63.73	2.29	+9.50	1.78	5.32	< .01
5	Analog PRE	7.13	0.47				
6	Analog POST	9.23	0.54	+2.10	0.52	4.04	< .01
7	Set-M PRE	5.13	0.29				
8	Set-M POST	5.73	0.40	+0.60	0.31	1.92	.1 > p > .05
9	I.Q.	109.33	2.12				

Table 2

Means and Standard Errors of All Variables for the High- and Low-Structuring Groups on the ROCK Concepts Structuring Task and Pre- to Post-Instructional Changes

	Variable	Mean	S.E.	PRE to POST Changes			
				Difference	S.E.	t	p
High-Structuring Group on ROCK Concepts (N = 10)							
1	Geol PRE	24.40	1.46				
2	Geol POST	29.70	1.74	+5.30	1.61	3.30	< .01
3	Geol % PRE	59.20	3.57				
4	Geol % POST	67.80	4.29	+8.60	3.04	2.82	< .05
5	Analog PRE	9.40	0.48				
6	Analog POST	10.40	0.81	+1.00	0.70	1.43	> .1
7	Set-M PRE	6.00	0.36				
8	Set-M POST	7.40	0.72	+1.40	0.58	2.41	< .05
9	I.Q.	116.30	3.91				
Low-Structuring Group on ROCK Concepts (N = 12)							
1	Geol PRE	20.00	1.18				
2	Geol POST	26.00	1.90	+6.00	1.35	4.45	< .01
3	Geol % PRE	48.75	2.88				
4	Geol % POST	59.58	3.73	+10.83	2.82	3.84	< .01
5	Analog PRE	5.67	0.72				
6	Analog POST	8.25	0.82	+2.58	0.83	3.11	< .01
7	Set-M PRE	4.42	0.48				
8	Set-M POST	4.25	0.35	-0.17	0.44	0.38	> .1
9	I.Q.	104.42	2.50				

Table 3

Significance of Difference between Means on Each Variable
for High- and Low-Structuring Groups
on the ROCK Concepts Structuring Task

	Variable	Difference between Means (High-Low)	S.E.	t	p
1	Geol PRE	4.40	1.86	2.37	$<.05$
2	Geol POST	3.70	2.62	1.41	$>.1$
3	Geol % PRE	10.45	4.54	2.30	$<.05$
4	Geol % POST	8.22	5.67	1.45	$>.1$
5	Analog PRE	3.73	0.90	4.13	$<.01$
6	Analog POST	2.15	1.16	1.85	$.1 > p > .05$
7	Set-M PRE	1.58	0.63	2.52	$<.05$
8	Set-M POST	3.15	0.75	4.16	$<.01$
9	I.Q.	11.88	4.50	2.64	$<.05$

Table 4

Means and Standard Errors of All Variables for the High- and Low-Structuring Groups on the MINERALS Concepts Structuring Task and Pre- to Post-Instructional Changes

	Variable	Mean	S.E.	PRE to POST Changes			
				Difference	S.E.	t	p
High Structuring Group on MINERALS Concepts (N = 9)							
1	Geol PRE	24.44	1.71				
2	Geol POST	30.33	1.85	+5.89	1.13	5.20	< .01
3	Geol % PRE	59.44	4.12				
4	Geol % POST	70.00	4.08	+10.56	4.35	2.43	< .05
5	Analog PRE	8.22	0.76				
6	Analog POST	11.00	0.83	+2.78	0.71	3.93	< .01
7	Set-M PRE	5.89	0.45				
8	Set-M POST	7.78	0.76	+1.89	0.61	3.09	< .05
9	I.Q.	117.44	4.08				
Low-Structuring Group on MINERALS Concepts (N = 10)							
1	Geol PRE	21.10	1.53				
2	Geol POST	27.60	2.66	+6.50	1.72	3.78	< .01
3	Geol % PRE	51.40	3.72				
4	Geol % POST	60.80	4.82	+9.40	2.71	3.46	< .01
5	Analog PRE	6.10	0.89				
6	Analog POST	8.50	0.91	+2.40	0.78	3.09	< .05
7	Set-M PRE	4.20	0.33				
8	Set-M POST	4.20	0.51	0			
9	I.Q.	108.50	3.18				

Table 5

Significance of Difference between Means on Each Variable
for High- and Low-Structuring Groups
on the MINERALS Concepts Structuring Task

	Variable	Difference between Means (High-Low)	S.E.	t	p
1	Geol PRE	3.34	2.29	1.46	> .1
2	Geol POST	2.73	3.29	0.83	> .1
3	Geol % PRE	8.04	5.54	1.45	> .1
4	Geol % POST	9.20	6.39	1.44	> .1
5	Analog PRE	2.12	1.18	1.80	.1 > p > .05
6	Analog POST	2.50	1.24	2.01	.1 > p > .05
7	Set-M PRE	1.69	0.55	3.06	< .01
8	Set-M POST	3.58	0.90	3.98	< .01
9	I.Q.	8.94	5.14	1.74	.1

Table 6

Analogies and Set-Membership Items with Significant Pre- to Post-Instructional Changes for the Total Group (N = 30)

		Proportion Correct PRE	Proportion Correct POST	χ^2 for Change	p
sediment is to sedimentary rock as sedimentary and igneous rock are to _____	heat and pressure metamorphic rock limestone and granite metamorphosis	.67	.83	5.00	<.05
C is to $CaCO_3$ as _____ is to compound	carbon molecule element atom	.40	.70	5.40	<.05
sea shell is to _____ as diamond is to carbon	natural calcium carbonate molecule atom	.20	.47	6.40	<.02

Cross out the word that does not belong with the other three:

crystalline structure	inorganic	naturally occurring	organic	.07	.38	6.23	<.02
crystal	ice	water	water vapor	.76	.52	7.00	<.01

Table 7

Analogies Items on Which High-Structuring Students Tend to Perform Better than Low-Structuring Students

		Group*	Proportion Correct High	Low	χ^2 for Difference	p
carbon is to atom _____ is to molecule	diamond	RI	.60	.17	4.43	<.05
	calcium carbonate	RF	.40	.25	0.57	N.S.
	compound	MI	.33	.20	0.43	N.S.
	element	MF	.44	.10	2.90	<.10
halite is to NaCl as table salt is to _____	NaCl	RI	.90	.42	5.51	<.05
	molecule	RF	.70	.42	1.77	<.20
	atom	MI	.77	.40	2.77	<.10
	cube	MF	.88	.60	2.04	<.20
mineral is to inorganic as sea shell is to _____	animal	RI	.80	.25	6.60	<.05
	crystal	RF	.80	.50	2.12	<.20
	organic	MI	.44	.40	1.17	N.S.
	naturally occurring	MF	.66	.40	1.35	N.S.
sea shell is to _____ as diamond is to carbon	natural	RI	.40	.08	3.12	<.10
	calcium carbonate	RF	.60	.33	1.56	N.S.
	molecule	MI	.33	.10	1.55	N.S.
	atom	MF	.66	.30	5.12	<.05
mineral is to _____ as bread is to made by humans	unnatural	RI	.90	.58	2.76	<.05
	flour	RF	.70	.58	.32	N.S.
	quartz	MI	1.00	.70	3.21	<.10
	natural	MF	.77	.70	0.15	N.S.

*R indicates groups identified on basis of ROCK Concepts
M indicates groups identified on basis of MINERALS Concepts
I indicates pre-instruction test
F indicates post-instruction test

Table 8

Set-Membership Items on which High-Structuring Students Tend to Perform Better than Low-Structuring Students

Cross out the word that does not belong with the other three:	Group*	Proportion Correct		χ^2 for Difference	p
		High	Low		
lava	RI	1.00	.55	5.97	< .05
limestone	RF	1.00	.91	.96	N.S.
sandstone	MI	.88	.66	2.68	< .20
shale	MF	1.00	.88	.27	N.S.
crystalline structure	RI	0.00	.18	2.01	< .20
inorganic	RF	.50	.09	4.30	< .05
naturally occurring	MI	0.00	.11	1.06	N.S.
organic	MF	.66	.11	5.58	< .02
landform	RI	1.00	.64	9.55	< .01
mineral	RF	.90	.64	6.39	< .05
rock	MI	.88	.88	0.00	N.S.
table salt	MF	.77	.66	.28	N.S.
carbon	RI	.10	0.00	1.15	N.S.
crystal	RF	.40	0.00	5.44	< .05
diamond	MI	.11	0.00	1.06	N.S.
graphite	MF	.44	0.00	5.14	< .05
compound	RI	.30	.09	1.49	N.S.
element	RF	.60	.09	6.11	< .05
mixture	MI	.44	0.00	5.14	< .05
solution	MF	.66	.11	5.58	< .02

*R indicates groups identified on basis of ROCK Concepts
M indicates groups identified on basis of MINERALS Concepts
I indicates pre-instruction test
F indicates post-instruction test

Table 8 (continued)

Cross out the word that does not belong with the other three:	Group*	Proportion Correct High	Low	χ^2 for Difference	p
crystal	RI	.70	.82	.40	N.S.
ice	RF	.70	.27	3.83	.05
water	MI	.77	.66	.28	N.S.
water vapor	MF	.77	.22	5.56	<.02
sedimentary rock	RI	1.00	.73	3.18	<.10
sandstone	RF	.90	.73	1.01	N.S.
mineral	MI	1.00	.66	3.60	<.10
limestone	MF	.77	.66	.28	N.S.

*R indicates groups identified on basis of ROCK Concepts
M indicates groups identified on basis of MINERALS Concepts
I indicates pre-instruction test
F indicates post-instruction test

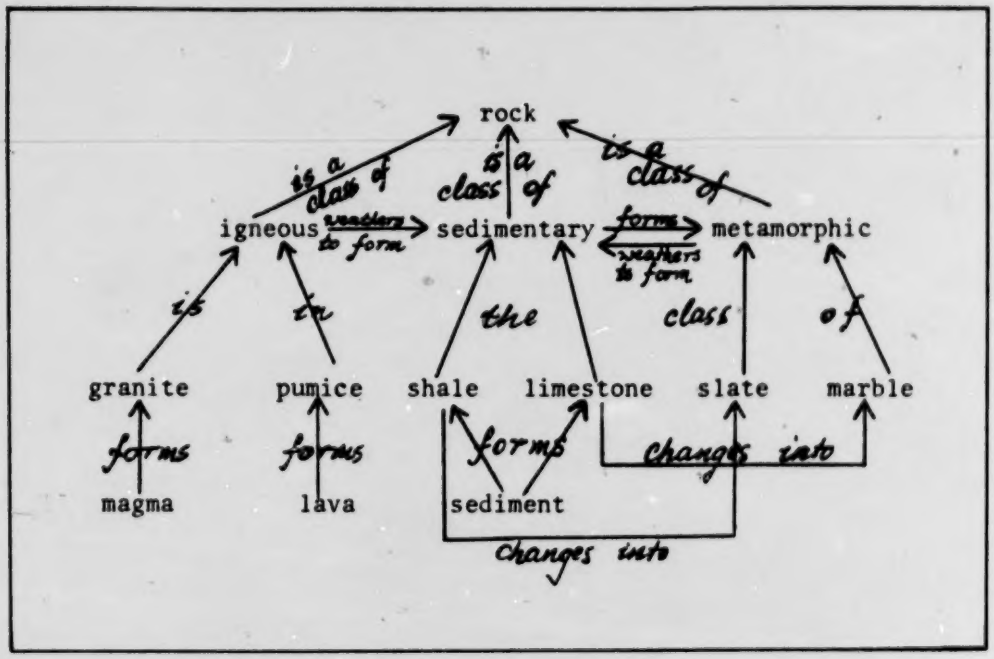
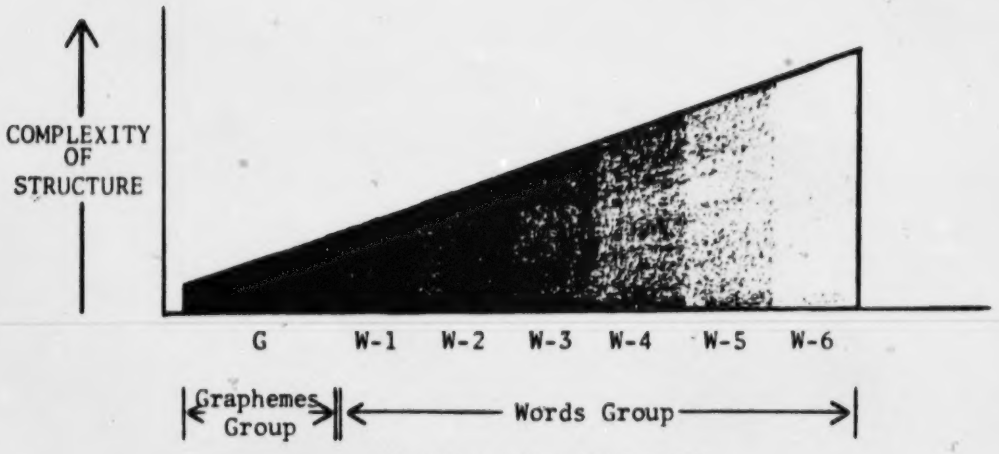


Figure 1

Integrated Structure Showing Hierarchical and Transformation Relations of the Thirteen Words in the ROCK Task



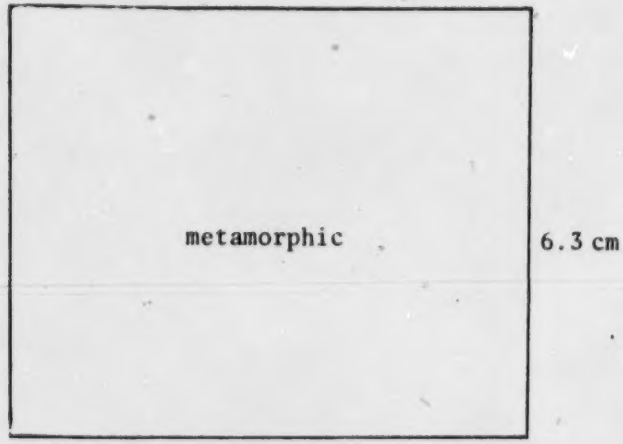
CLASSES OF STRUCTURES

CLASS	ATTRIBUTES OF THE CLASS
W-6	integration of hierarchical structure and transformational structure into a single structure
W-5	hierarchical structure plus fragment of transformational structure
W-4	hierarchical structure or transformational structure
W-3	fragments of the hierarchical and/or transformational structures
W-2	two or more words related by a single technical or general usage label
W-1	two or more words, unspecified relationships

G	two or more words related by a single morphological characteristic

Figure 2

Attributes and Classes for ROCK Structures



Practice Task	ATOM Task	MINERAL Task		ROCK Task	
body	atoms	C	inorganic solid substances	granite	metamorphic
ears	chemical compounds	$CaCO_3$	limestone	igneous	pumice
eyes	chemical elements	calcite	mineral	lava	rock
face	chemical substances	calcium carbonate	NaCl	limestone	sediment
foot	molecules	carbon	shells of sea animals	magma	sedimentary
heel		diamond	substances with a characteristic crystalline structure	marble	shale
metatarsus		graphite	substances with a definite chemical composition		slate
nose		halite	naturally occurring substances		
soul			table salt		
toes					

Figure 3

Sample Card and Words Used in Concept Structure Tasks

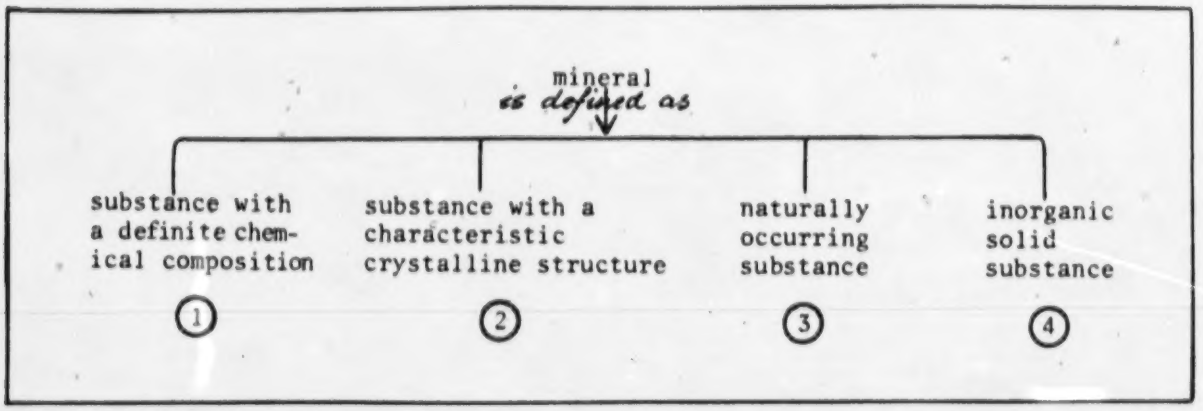


Figure 4

Mineral Definition Structure

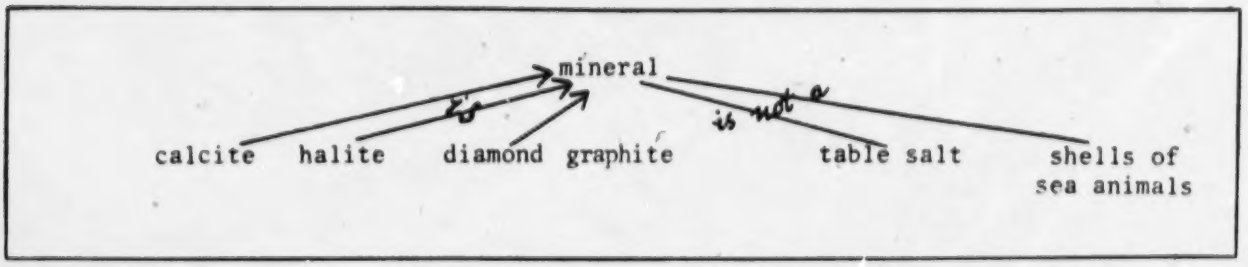


Figure 5

Mineral Class Membership and Non-Membership Structure

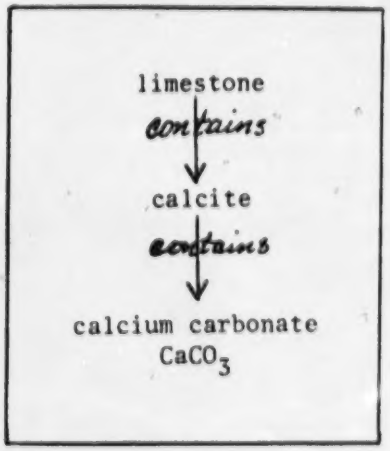
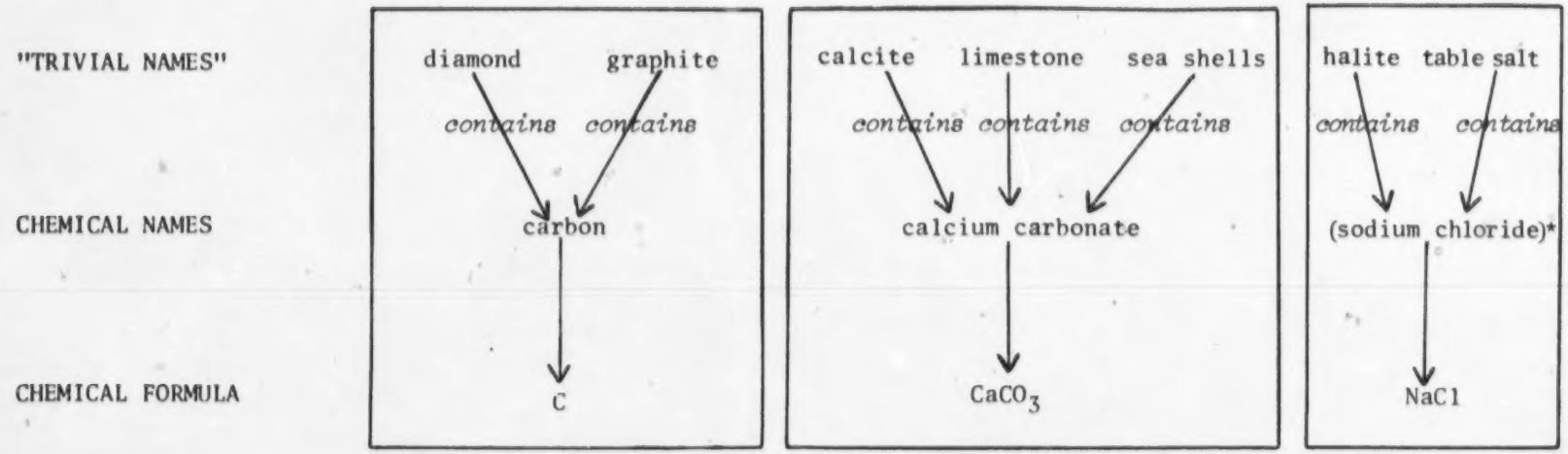


Figure 6

Rock Composition Structure



*not included in the sort

Figure 7

Chemical Relations Structure

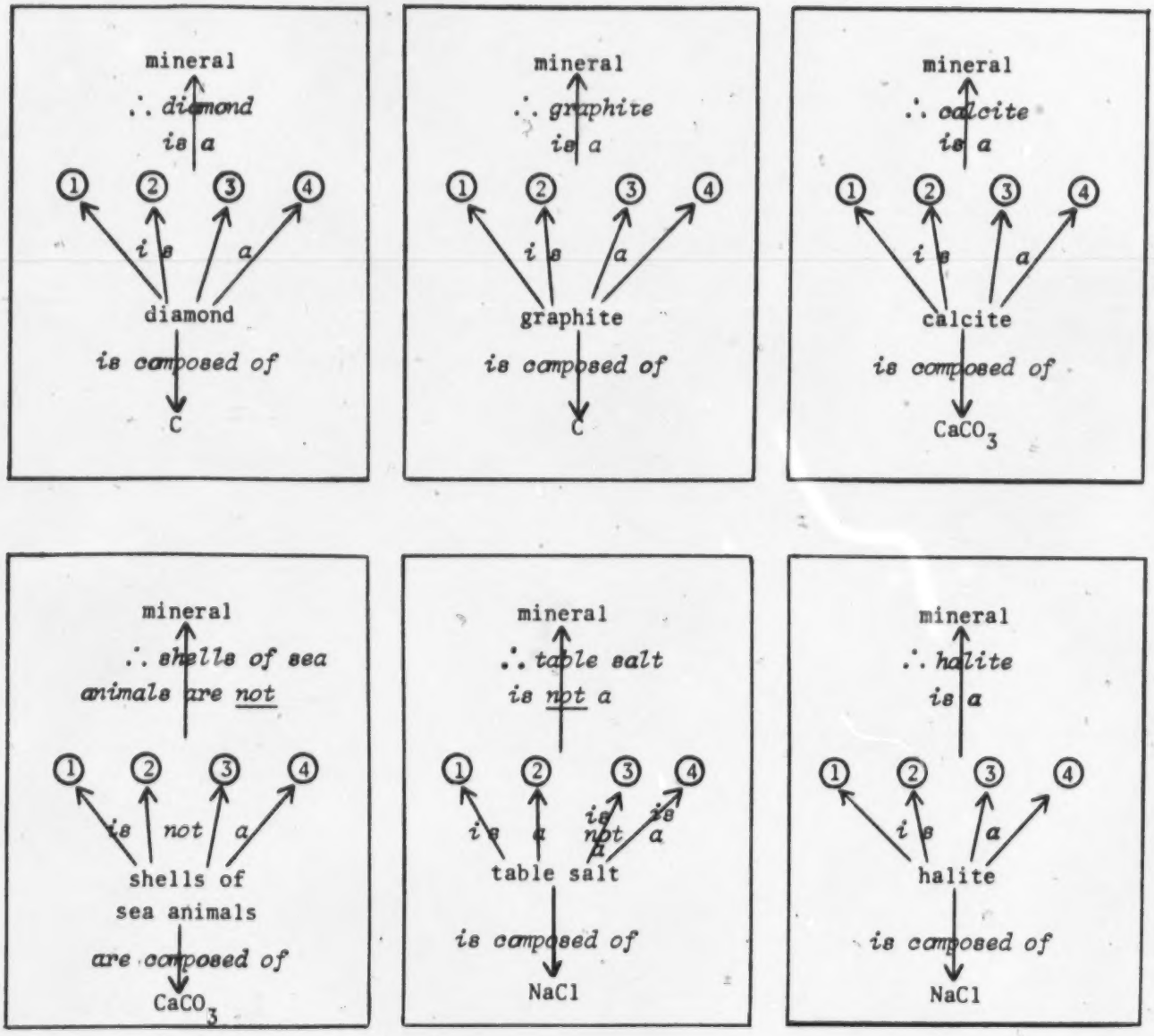


Figure 8

Origins of Chemical and Geological Distinction

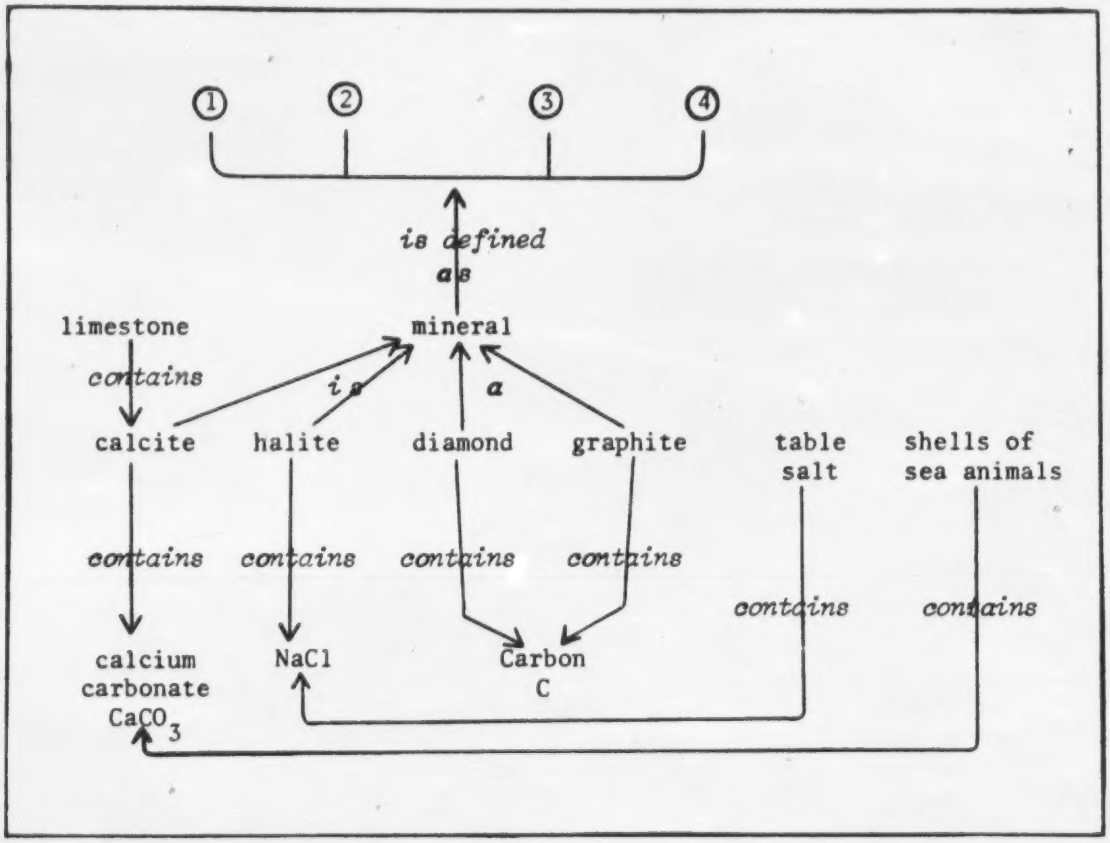
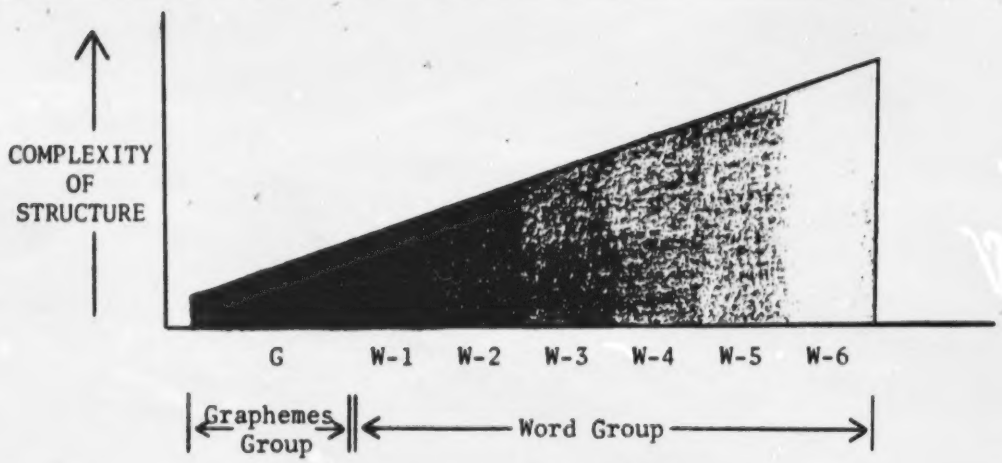


Figure 9

Integrated Structure



CLASSES OF STRUCTURES

CLASS	ATTRIBUTES OF THE CLASS
W-6	integration of relationships among three or more terms integrated with characteristics of minerals
W-5	relationships among four terms, ex. limestone(rock) ⟷ calcite(mineral) ⟷ calcium carbonate(chemical name) ⟷ $CaCO_3$(chemical formula)
W-4	relationships among three terms: diamond ⟷ C ⟷ crystalline structure
W-3	relationship between two terms: table salt ⟷ NaCl
W-2	two or more words related by a single technical or general usage label, ex: group of minerals, group of non-minerals or group of characteristics of minerals
W-1	Two or more words, unspecified relationships

G	two or more words related by a single morphological characteristic

Figure 10

Attributes and Classes for MINERAL Structures

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